Received: 15 April 2019 | Revised: 13 September 2019 | Accepted: 16 September 2019

DOI: 10.1002/wat2.1401

WIREs WATER WILEY

OVERVIEW

Evaluation and communication of pluvial flood risks in urban areas

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Abstract

The increase of pluvial flooding has long been discussed to be a most probable outcome of climate change. This has raised the question of necessary consequences in the design of urban drainage systems in order to secure adequate flood protection and resilience. Due to the uncertainties in future trends of heavy rainfall events, the awareness of remaining risks of extreme pluvial flooding needs to be roused at responsible decision makers and the public as well leading to the implementation of pluvial flood risk management (PFRM) concepts. The state of two core elements of PFRM in Germany are described here: flood hazard and risk evaluation and risk communication. In 2016 the guideline DWA-M 119 has been published to establish city-based PFRM concepts in specification of the European Flood Risk Management Directive (EU 2007). As core elements, the guidelines recommend a site-specific analysis and evaluation of flood hazards and potentials of flood damages to create flood hazard and flood risk maps. In the long run, PFRM needs to be established as a joint community effort and a requirement for more flood resilience. The risk communication within the administration and in the public requires a comprehensible characterization and classification of heavy rainfall to illustrate event extremity. The concept of a rainstorm severity index (RSI) instead of statistical rainfall parameters appears to be promising to gain a better perception by affected citizens and non-hydrology-experts as well. A methodical approach is described to specify and assign site-specific rainfall depths within the severity index scheme RSI12.

This article is categorized under:

- Engineering Water > Sustainable Engineering of Water
- Engineering Water > Planning Water
- Engineering Water > Methods

KEYWORDS

flood resilience, flood risk communication, pluvial flooding, probable maximum precipitation, rain storm severity index RSI12, urban flooding

1 | INTRODUCTION

Urban flooding caused by severe pluvial rainstorms has been reported for an increasing number of locations throughout the world (CMP, 2012; GDV, 2016; Grünewald, 2009; Grüning & Grimm, 2015; URBAS, 2008; Villordon & Gourbesville, 2014). Quite often the public relates the observation of major flooding to the effects of global warming and climate change. This presumption is supported by the reports of IPCC and the assessment that the increase of extreme weather events between now and 2050, and further on to 2100 is "extremely likely … in the majority of areas" (IPCC, 2008). As a consequence, climate factors >1 as the ratio between expected future and present rainfall depths are proposed to be included in design criteria for urban drainage systems and flood protection measures (Arnbjerg-Nielsen, 2008; Zhou, Mikkelsen, Halsnaes, & Arnbierg-Nielsen, 2012).

Most importantly, the discussion about possible impacts of climate change triggered the awareness of high uncertainty in future rainstorm patterns and the risks of urban flooding (Ashley, Balmforth, Saul, & Blanskby, 2004; Richardsen, 2002; Sun, Leonhardt, Bertrand-Krajewski, & Rauch, 2014). Consequently, it has been proposed to establish flood risk management for urban drainage systems by applying systematic assessment of pluvial flood hazards and potential adverse consequences of flooding (Schmitt, 2011; Zhou et al., 2012). The assessment and management of flood risks are outlined in the European Directive 2007/60/EC (EU, 2007), focusing on fluvial flooding and floods from the sea in coastal areas.

In Germany, the design of urban drainage systems has been based on design rainfall events with specified statistical return periods in the range of 1–5 years and derived design sewer flow for both combined and storm sewers to run full. Above that level, urban drainage systems have been expected to provide flood protection for rainfall events up to a 30-year return period at most, according to the European Standard EN 752 (CEN 1996). The comparison of rainfall intensities in the range of design and flood protection concepts with rainfall events observed most recently reveal the large gap between the expected protection against flooding and the actual risk of flooding by extreme rainfall events. In contrast to river flooding pluvial flooding can (theoretically) occur at any location within a city. It cannot be interrelated directly to some topographical or landscape features or to the built environment. Thus, city-wide flood hazard and risk analysis need to be carried out including all the impact factors within the natural and built environment possibly affecting the occurrence of flooding as well as vulnerability factors (location and exposition of estates, facilities, critical infrastructures, etc.). Of course, flood hazard and risk analysis must consider a much wider range of rainfall intensities well above the design criteria. The graduated approach of different methods of flood hazard analysis outlined in the German guidelines DWA-M 119 (Technical Bulletin) will be presented in Section 3.

Profound pluvial flood hazard and risk analyses, detailed coupled 1D/2D-modeling as well as GIS-based topographic approaches, require a reliable working base. This is ensured nowadays by advanced simulation hardware and software and, most important, by the availability and provision of sufficiently detailed spatial data, especially high-resolution digital surface models (DSMs). Besides, a systematic evaluation of methods and the development of specific recommendations for the application need further effort (see e.g., HSB, 2017; Hürter, 2018; Scheid, 2018).

Beside this, the communication of flood risks is a second core element of urban flood risk management, as citizens are directly affected by urban flooding as inhabitants and/or owners of flooded estates. Risk communication includes both, providing information on specific locations of high flood hazards and explaining the character of extreme rainstorm events. It is doubtful that the public actually perceives the meaning of return periods or the recurrence probability, used by hydrologists to rank heavy rainstorms (Grisa, 2013). Nor will the implication of different return periods be fully understood by city, traffic, and landscape planners. They need to be involved in the implementation of effective, preferably multipurpose flood protection measures in urban areas and as crucial stakeholders for adaptation measures towards more flood resilient cities.

Consequently, Grisa (2013) suggests ranking extreme storms by severity rather than by rarity. His concept to assign a rainstorm severity index (RSI) includes the features return period, duration, and intensity of heavy rainfall events. The use of index-based ranking instead of science-based hydrologic parameters is emphasized in several respects. Villordon and Gourbesville (2014) propose a vulnerability index to provide a better perception of social vulnerabilities and risks of urban flooding in the community. Batica, Gourbesville, and Hu (2013) describe a flood resilience index for different spatial scales (from city to parcel) to enhance flood risk management. Ramos, Creutin, and Leblois (2005) have developed severity diagrams and graphs to visualize the spatial dimension of storm severity and illustrate the strong spatial variability for three heavy rain events in the city of Marseille. Müller and Kaspar (2014) propose a weather extremity index to evaluate the extremeness of heavy rain events in their spatiotemporal distribution. More closely related to pluvial flood risk managem (PFRM), Schmitt et al. (2018) have established the RSI concept RSI12.

The authors assign rainfall depths to severity index values from 1 to 12, based on site-specific heavy rainfall statistics. This concept will be described in Section 4.

2 | FROM DRAINAGE EXPERT DESIGN TO FLOOD RISK MANAGEMENT

For many years the design of urban drainage systems had been based upon concepts of design storm frequencies. Surface runoff and sewer flow values have been computed for site-specific rainfall intensities provided by national weather services or databases (IDF curves) and required sewer pipe slope and diameters have been selected. Only little consideration had been given to the possible occurrence of sewer flooding and resulting damages, neither in general nor regarding to site-specific factors of flood hazards.

In Germany, only in early 1990 the Federal Court BGH ("Bundesgerichtshof") issued a principal judgment that it is unreasonable to subject residents to frequent sewer flooding, in extreme cases, once per year. BGH stated that urban drainage systems should be designed to allow much smaller frequencies of sewer flooding (BGH, 1989). In the aftermath, the European Committee for Standardization (CEN) provided hydraulic performance criteria in the European Standard EN 752 (CEN 1996) and recommended both, design storm frequencies and distinct frequencies of flooding.

2.1 | Main features of European Standard EN 752

The European Standard EN 752 "External Drain and Sewer Systems," approved by CEN (Comité Européen de Normalisation), is applicable to drainage systems designed essentially for gravity flow. CEN member nations—the nations of the European Union plus Iceland, Norway, and Switzerland—are obliged to adopt this standard as a national regulation without alteration. CEN first provided hydraulic performance requirements in 1996 (EN 752-2, CEN 1996) and published revised versions in 2006 and most recently in 2017 (CEN 2017). As a general statement, EN 752 pointed out that the major criterion of hydraulic performance of urban drainage systems is the level of flood protection provided.

For the design of small drainage systems, EN 752 lists hydraulic performance criteria in terms of design storm frequencies. Sewers are designed for a peak flow to run full, with rainfall runoff derived from local rainfall intensities. The distinction in storm frequencies between rural, residential and industrial areas, and city centers, respectively, reflects the different values of buildings and installations as well as potential (monetary and non-monetary) damages or functional impediments caused by flooding. EN 752 points out that in addition, the local situation, for example, pipes connected to building basements and the chance of basement flooding during times of sewer surcharge, might lead to lower design frequencies.

Most recently, CEN has updated the criteria of flood protection. The 2017 version of EN 752 (CEN 2017) lists sewer flooding criteria where the return periods of sewer flooding are linked to possible impacts of flooding and vary between 1 year (very low impacts), 5–10 years (medium impacts), and 50 years in case of very high impacts, for example, related to critical infrastructure. Table 1 shows the recommended sewer flooding criteria together with example locations with distinct potentials of flood impacts.

For small development plans, a relatively simple approach is recommended using local rainfall data corresponding to the design storm frequencies in Table 1, and rational method/time offset types of design procedures. Sewers are designed to remain below theoretical pipe flow (free of surcharge) at peak flow rate. For larger developments and drainage systems with complex hydraulic flow patterns (e.g., with loops, backwater effects), the level of flood protection should be directly assessed by hydraulic simulations, based on the criteria recommended in Table 1.

2.2 | The analysis of flooding in urban drainage systems

Flooding in urban areas due to the failure of drainage systems causes large damage at buildings and other public and private infrastructure. Besides, street flooding can limit or completely hinder the functioning of traffic systems and has indirect consequences such as loss of business and opportunity. The expected total damage—direct and indirect monetary damage costs as well as possible social consequences—is related to the physical properties of the flood, that is, the water level above ground level, the extend of flooding in terms of water volume escaping from or not entering the

TABLE 1 Examples of design sewer flooding criteria for standing floodwater according to EN 752 (2017)

		Examples of design sewer flooding frequency	
Impact	**Example locations**	**Return period** ***years***	**Probability of exceeding in any 1 year**
Very low	Roads or open spaces away from buildings	1	100%
Low	Agricultural land (depending on land use, e.g., pasture, arable)	2	50%
Low to medium	Open spaces used for public amenity	2	30%
Medium	Roads or open spaces adjacent to buildings	5	20%
Medium to high	Flooding in occupied buildings excluding basements	10	10%
High	Deep flooding in occupied basements or road underpasses	30	3%
Very high	Critical infrastructure	50	2%

drainage system, and the duration of flooding. With sloped surfaces even the flow velocity on the surface has an impact on potential flood damage.

Linking drain system hydraulic performance requirements directly to the frequency of flooding demands a clear definition of flooding and a distinction from the state—or different stages—of surcharge. EN 752-1 (1995) defines "flooding" as a "condition where wastewater and/or surface water escapes from or cannot enter a drain or sewer system and either remains on the surface or enters buildings." The qualification "…or enters buildings" distinguishes "flooding" from "surface flooding."

Distinct from flooding, the term "surcharge" is defined as a "condition in which wastewater and/or surface water is held under pressure within a gravity drain or sewer system, but does not escape to the surface to cause flooding." Extended surcharge conditions may eventually lead to a rise of water levels to the surface where water either escapes from the sewer system or prevents surface water from entering the sewer system.

Flooding in urban drainage systems as defined above may occur at different stages of hydraulic surcharge as shown in Figure 1, depending on the drainage system (separate or combined sewers), general drainage design characteristics as well as specific local constraints. When private sewage drains are directly connected to the public sewer system without backwater valves, the possible effects of hydraulic surcharge depend on the levels of the lowest sewage inlet inside the house, the sewer line and the water level during surcharge, respectively. Whenever the water level in the public sewer exceeds the level of gravity inlets in the house below street level, flooding inside the house will occur due to backwater effects. In such a case flooding is possible without experiencing surface flooding.

In the same way, hydraulic surcharge in the sewer system might produce flooding on private properties via storm drains or basement drains, when their inlet level is below the water level of the surcharged sewer. In both cases, the

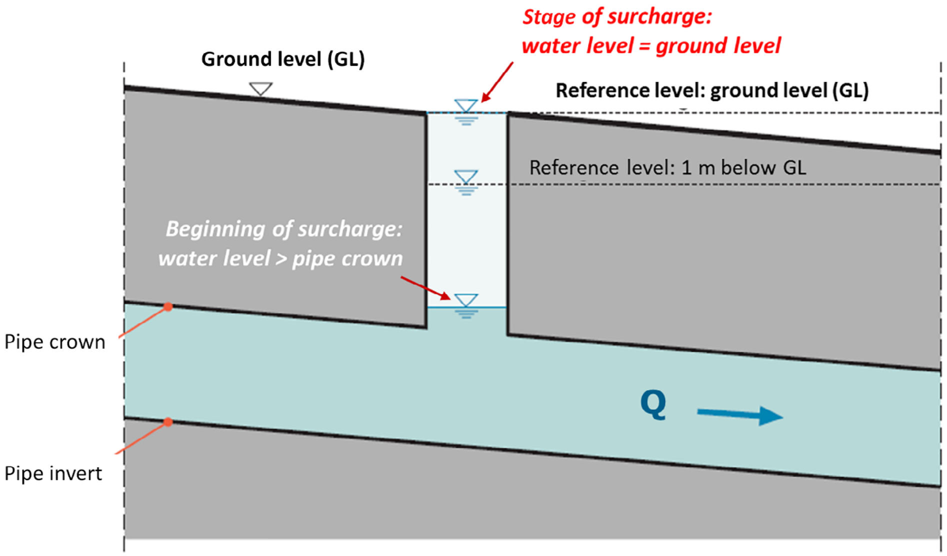

FIGURE 1 Stages of sewer surcharge

prediction of flooding, being linked directly to the level of inlets versus water level (pressure height) in the sewer by hydrodynamic sewer flow simulations is quite reliable, assuming the availability of physical data of the private drains and the public sewer system.

Nowadays, a well-founded database is available in most cities as a prerequisite for detailed analysis of potential surface flooding, as required in EN 752 and in DWA-A 118. High-resolution DSMs (with more than 1 data point per m^2) allow the application of appropriate GIS-based methods or coupled runoff simulations. Depending on the method applied, flood-prone areas as depressions and surface flow paths can be identified and—related to defined rainfall frequencies—simulated flooding parameters as water depths, velocities and discharges provide precious detail information about local circumstances and characteristics of flooding (e.g., Hürter, 2018; Scheid, 2018; see Section 3.2).

3 | ELEMENTS OF PLUVIAL FLOOD RISK MANAGEMENT ACCORDING TO DWA-M 119

3.1 | Pluvial flood risk management—a joint community task

The discussion about future impacts of climate change and the possible increase of extreme rainfall and flooding events has raised the question of necessary consequences in urban flood protection concepts. It has become common sense that for any future trend in the occurrence of extreme rainfall events the underground sewer system will not be able to provide enough capacity to either convey or store the instantaneous surface runoff during torrential rainfall as observed lately. Consequently, the introduction of lumped safety factors in sewer design does not appear as a promising approach. The uncertainty in future trends of heavy rainfall events demands for more flexibility and adaptiveness in drainage concepts. At the same time, the awareness of remaining risks of extreme storm events and flooding needs to be roused at both, responsible political decision makers, especially in the municipalities, and the public as well. The responsibility of private house owners to reduce or limit potential damage of flooding has to be communicated.

Figure 2 shows the approach of a shared responsibility and flood risk management tasks within the local community of "stakeholders" as suggested by the German Water Association [DWA] (2008). It is based on the understanding, that the underground sewer system, supported by source-based storm water best management practice, provides a certain level of flood protection, to be characterized as "drainage comfort." This applies for rainfall events in the range of typical design storm frequencies as shown in Figure 2. In order to provide effective flood protection for a second level of rainfall intensities, conventional drainage systems need to be supplemented by effects of temporary runoff retention, storage and/or discharge using traffic and open space areas that allow temporary surface ponding without damages or functional impairment. This might need local flood protection measures for distinct buildings and/or infrastructure installations. On a third level of rainfall events, it is accepted that full flood protection would no longer be possible and

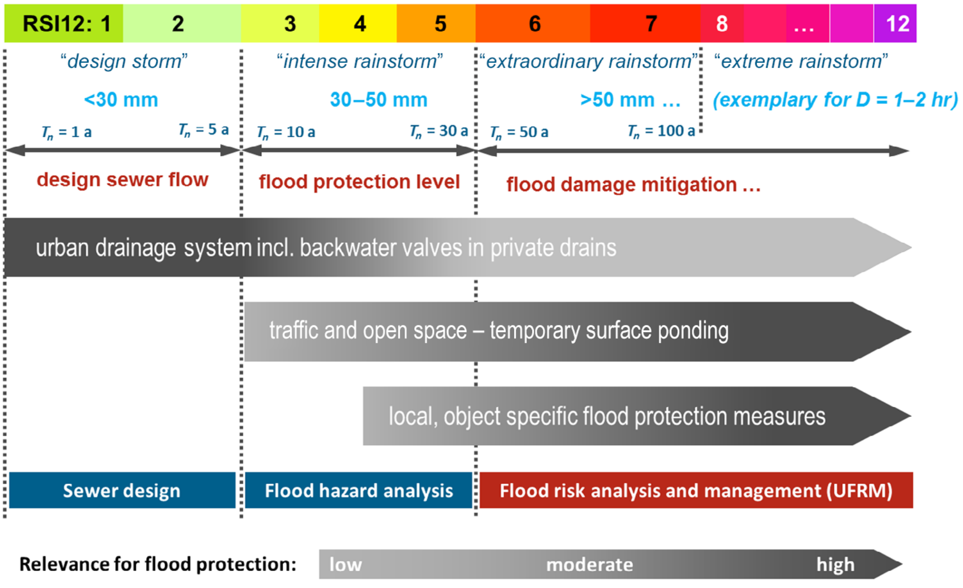

FIGURE 2 Impact categories of urban drainage and pluvial flood risk management concerns—as a joint community task (own illustration according to DWA (2008) and Schmitt et al., 2018)

flood damage mitigation must be accomplished by resilient surface structures and local object-based flood protection for hazardous areas, buildings and infrastructure.

The rainfall depths shown in Figure 2 refer to a 1–2 hr rainfall event (according to DWD, 2017). They illustrate that typically designed sewer systems should handle rainfall events with up to about 30 mm within 1–2 hr duration without surcharge leading to surface ponding, for a range of 30–50 mm the concern of effective flood protection would apply. Extreme rainfall events delivering rainfall depths well above 50 mm within 1–2 hr would demand for actions of flood mitigation.

Major specifications of the European Flood Risk Management Directive (EU, 2007) have been picked up and adapted for the implementation of a modular flood risk analysis for urban areas and drainage systems, by the German Technical Bulletin DWA-M 119 (DWA, 2016), as shown in Figure 3.

3.2 | Main features of DWA-M 119

The major components of PFRM as addressed in DWA-M 119 are a site-specific flood hazard analysis, a general or object-based damage potential analysis, a flood risk evaluation as a synthesis out of it, recommendations for flood risk communication and a list of possible actions of flood prevention, protection and mitigation. Aspects of their practical application are addressed in Section 4.

3.2.1 | Methods of flood hazard analysis

As a major topic DWA-M 119 presents a range of methodical approaches to carry out a site-specific flood hazard analysis and describes their specific features and possible scope of application (Figure 4). A clear distinction is made between topographical methods and hydraulic simulations as the two most important approaches for practical application. Both approaches are briefly outlined below. GIS-based topographical analyses identify potential flow paths and surface depression ponding areas (sinks) without specifying rainfall data as system load. Detailed hydraulic-based methods carry out dynamic flow-routing for specified rainfall intensities and provide load-dependent hazard information. For both methods, an evaluation scheme is presented with four distinct categories of flood hazard (low – moderate – high – very high), based on the specific outcome of a method's application (e.g., water level, surface velocity, discharge).

GIS-based topographical analyses are carried out based on DSMs represented in grid patterns and land register information. They provide information for a fast, city-wide identification of flooding areas for system loads, where flow capacity of the underground sewer system is clearly exceeded. They are generally recommended as a first approach towards the establishment of flood hazard maps. Local sinks being identified as major flood prones are to be understood as a worst-case situation. The local sinks should be represented in distinct zones of different water depths (Scheid, 2018).

2D-hydraulic simulation models describe the processes of surface flow and flooding in their spatial and temporal distribution. The coupling of a 2D-surface flow model with a 1D-sewer flow model allows the permanent representation

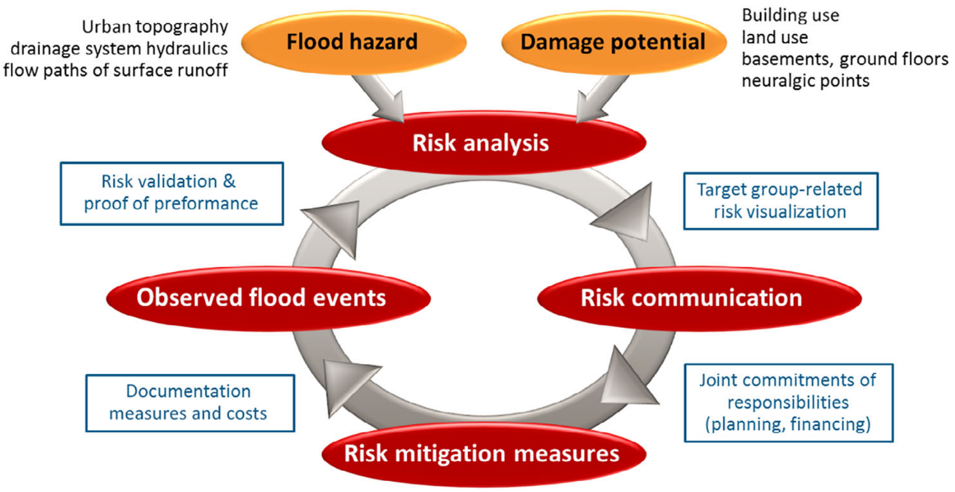

FIGURE 3 Pluvial flood risk management cycle (adapted from EU 2007 own illustration according to Krieger & Schmitt, 2015)

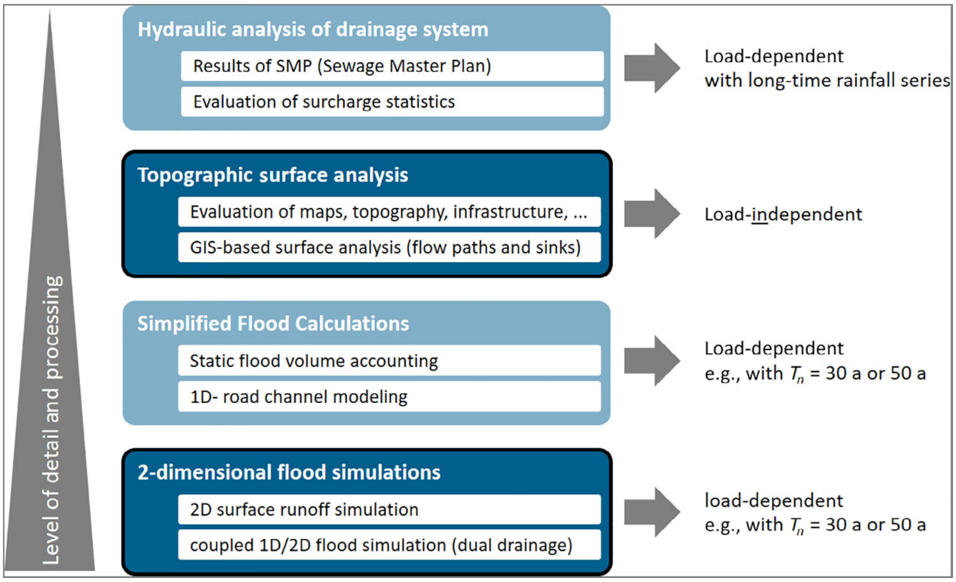

FIGURE 4 Methods of flood hazard analysis (own illustration according to DWA, 2016 and Krieger & Schmitt, 2018)

of flow exchange between surface and sewer flow at street inlets and manholes. This method has been characterized as dual-drainage modeling (e.g., Djordjević, Ivetic, Maksimović, & Rajcevic, 1991; Schmitt, Thomas, & Ettrich, 2004). 1D/2D-models are applied for detailed flood hazard analysis focused on specific hot spots of urban flooding. They require a sophisticated data preparation, model adaption, and high computational effort. For the coupling of surface and sewer flow it is strongly recommended to include street inlets as major points of water exchange during flooding (Hürter, 2018).

3.2.2 | Methods of damage potential analysis

A profound risk analysis consists of the two components flood hazard and vulnerability analyses (see e.g., United Nations International Strategy for Disaster Reduction [UNISDR], 2004). However vulnerability, being defined as "the conditions determined by physical, social, economic, and environmental factors or processes, which increase the susceptibility of a community to the impact of hazards" (UNISDR, 2004), is not to be adequately described in general and for a city-wide analysis of buildings and infrastructure facilities. This would require building-specific information in different dimensions (physical, socio-cultural, economical, and ecological). As a substitute, DWA-M 119 introduces the potential of flood damages as the total of all tangible and intangible damages and impacts of flooding, possibly expressed in monetary terms and including consequential economic losses. Potential damages and losses again are to be assessed as a rough estimate only. For existing buildings these estimates can be based on type of use information displayed in land register database. Individual, site-specific object values for a more detailed flood risk assessment in general are not available. The results might be expressed in damage categories from "low" to "high."

Based on the Technical Bulletin DWA-M 119, systematic hazard and risk analyses have been carried out in Germany and quite some municipal PFRM concepts have been developed. The current state of this development is explained below.

4 | STATE OF IMPLEMENTATION OF PLUVIAL FLOOD RISK MANAGEMENT CONEPTS IN GERMANY

4.1 | General survey aspects

In August 2018, a survey published by Krieger and Schmitt (2018) showed that quite a number of German cities have already implemented a PFRM concept or at least carried out thorough flood hazard analysis as the major component and basis for further actions to be taken.

In the survey 17 mid-size and metropolitan cities in Germany (in total about 12 Mio. inhabitants) have been addressed with questions about their specific program and actions taken towards a PFRM according to DWA-M 119. The answers showed that action has been initialized mostly by the municipal drainage department or wastewater utilities. Fourteen of 17 cities have already finished a city-wide survey or detailed analysis of flood hazards. However, only three cities have carried out a flood damage or vulnerability analysis to join the results and generate flood risk maps as mentioned in the European Flood Risk Management Directive (EU-2007). This clearly indicates the gap in both, data availability and methodical approaches between flood hazard and vulnerability analysis.

4.2 | Methods applied in flood risk analysis

The survey indicates a clear methodical preference for investigations based on topographical analysis. Both, the data needed and the corresponding software programs, are a widely used and easy to handle in terms of DSM applications, producing city-wide flood hazard maps. However, topographical analysis methods only provide general information on preferred surface flow paths and surface depressions where water ponding would start. These results are not linked to a specified rainfall event. There is no indication at what point of system load surface flow and/or water ponding would start and to what extension, respectively.

Six of 17 cities have applied a hydraulic 2D-surface runoff simulation. These methods require a detailed DSM in high resolution (1–4 points per m^2 of surface area) and the simulation can be carried out for different system loads, for example, specifying a whole range of rainfall depth and duration. The same holds true for the most sophisticated method of hydraulic 1D/2D-simulation based on coupled dual drainage concepts, allowing the permanent interaction of surface and sewer flow, whenever sewer surcharge occurs. Due to the required computing capacity, only one mid-size city has applied this sophisticated method so far (Krieger & Schmitt, 2018).

Depending on the size of the city area and the possibility to create subcatchments along topographical water divides, some of the cities have started the analysis in parts of the city, others have covered the whole city area. Also, in several cities the start of the hazard analysis has been initiated within (partly) funded research programs.

It has already been mentioned that only in three cities a city-wide corresponding analysis of potential flood damages and vulnerability has been carried out. Others have focused their investigations on single hot spots of flooding as identified in the hazard analysis.

4.3 | Data availability and data processing effort

Nowadays, digital elevation models with sufficiently high spatial resolution are available for most cities in Germany. However, the participants in the survey clearly indicate that the creation of a DSM including the built environment on the surface within cities requires quite some effort. Quantifications of time needed and resulting costs have not been stated and would be difficult to generalize anyway. It should be stated though, that only based on accurately established DSMs flood hazard analysis can produce reliable results.

4.4 | Risk communication

The communication of flood risks is seen as a core element of risk management in order to raise the awareness for flood hazards and the necessity of preventive actions, on both, the community and private level. As shown in Figure 5, target groups of flood risk communication are local decision makers, private house owners and the media as a multiplicator of information and hazard awareness (Krieger & Schmitt, 2018).

The survey indicates that risk communication has not been a major concern of flood risk management so far. Six of the 17 cities indicate to have concentrated on internal communication within the city administration and specific departments (e.g., city development, traffic and green infrastructure planning, disaster control emergency management). Only five cities have started to provide selective information for possible affected private house owners. Some cities provide more general information about their activities in the field of flood hazard and risk analysis via local and social media. Others have been prompted by the occurrence of pluvial flooding to spread more general and clarifying information on flood hazards in the newspaper or in citizen councils. The city of Cologne has published hazard maps

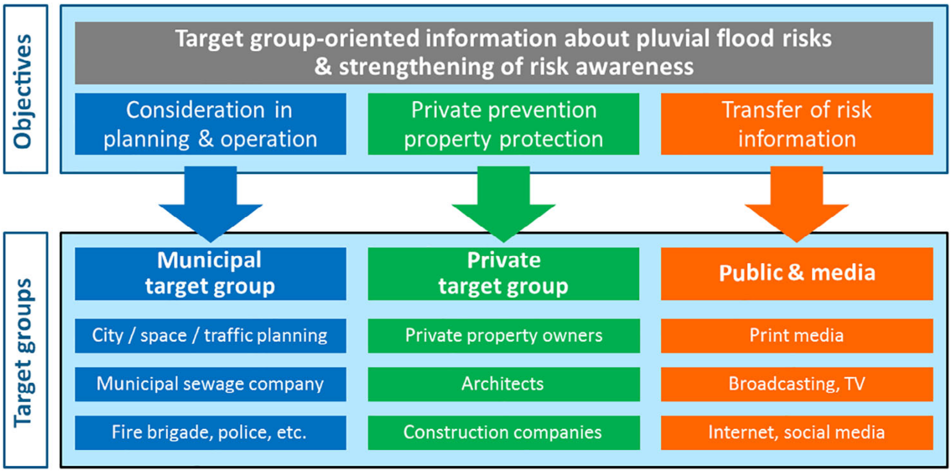

FIGURE 5 Objectives and target groups of flood risk communication (own illustration according to Krieger & Schmitt, 2018)

providing parcel-related flood hazard information derived for three distinct rainfall intensities. In general, city managers seem to still question whether and how the information of flood hazard or risk maps should be made available. This is at least partly due to legal uncertainties how to serve the obligation to supply information on one hand and the protection of data privacy on the other hand.

One specific aspect of flood risk communication is further discussed below.

5 | RISK COMMUNICATION VIA RAINSTORM SEVERITY INDEX

As citizens are directly affected by urban flooding, either as inhabitants or owners of flooded estates, communication of flood risks is a core element of urban flood risk management. Risk communication includes both, providing information on specific locations of high flood hazards and explaining the character of extreme rainstorm events. It is doubtful that the public actually perceives the meaning of return periods or the recurrence probability, used by hydrologists to rank heavy rainstorms. Nor will the implication of different return periods be fully understood by city, traffic and landscape planners. They need to be involved in the implementation of effective, preferably multipurpose flood protection measures in urban areas.

As a consequence, Grisa (2013) suggests ranking extreme storms by severity rather than by rarity. His concept to assign a RSI includes the features return period, duration and intensity of heavy rainfall events. The use of index-based ranking instead of science-based hydrologic parameters is emphasized by Villordon and Gourbesville (2014), proposing a vulnerability index to provide a better perception of social vulnerabilities and risks of urban flooding in the community. Ramos et al. (2005) have developed severity diagrams and graphs to visualize the spatial dimension of storm severity and illustrate the strong spatial variability for three heavy rain events in the city of Marseille. Müller and Kaspar (2014) propose a weather extremity index to evaluate the extremeness of heavy rain events in their spatiotemporal distribution.

In the following, a general classification used by the German Weather Service is mentioned before focusing on the RSI concept RSI12 suggested by Schmitt et al. (2018), as shown in Figure 6. They assign rainfall depths to severity index values from 1 to 12, based on site-specific heavy rainfall statistics. Its application will be illustrated using German rainstorm databases.

5.1 | Classification of German Weather Service

The German Weather Service applies threshold values for a nationwide classification of heavy rainfall events in his weather hazard warnings. The term "heavy rainstorm" ("Starkregen") applies to storm events with frequencies below 0.5 per year. Heavy rainstorms are further classified as "severe rainstorm" above 25 mm (1 hr duration) and 35 mm (6 hr), respectively. They would be classified as "extremely severe rainstorm" above 40 mm (1 hr) and 60 mm (6 hr), respectively. It should be noted that in the last decade quite some events with rainfall depths well above 100 mm in the

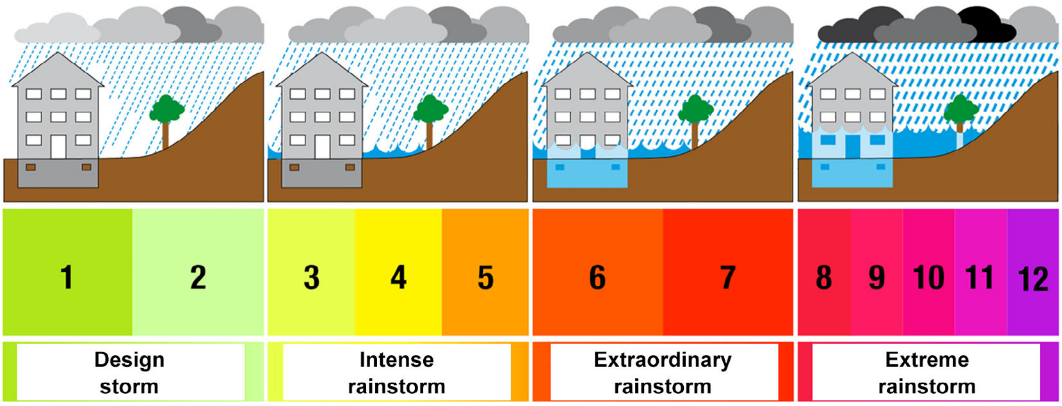

FIGURE 6 RSI12 concept for the purpose of pluvial flood risk communication (Schmitt et al., 2018)

1–2 hr range have been observed in Germany. Here, the events' extremity would not be expressed evidently by the cited classifications.

5.2 | Rainstorm severity index concept RSI12

An adaptation of Grisa's RSI concept has been suggested for urban flood risk management and communication in Germany as RSI12 concept by Schmitt (2014, 2015, 2016). Here, distinct RSI values between 1 and 7 directly correspond with return periods of rainstorm events up to the 100-year return period for selected rainfall durations. As an anchor and reference value, RSI 7 is pinned to the 100-year return period rainfall depth. Severity index values 8–12 are intended to provide a distinct characterization of rainfall depths well above the 100-year rainfall event.

5.2.1 | Assigning rainstorm severity index

The assignment of RSI values as suggested in Schmitt (2014, 2015, 2016) reflects the design storm and flooding frequencies proposed in the European Standards EN 752 (CEN, 2008) to assess the hydraulic performance of urban drainage systems and corresponding categories of heavy rain events as suggested in (DWA, 2016):

- RSI 1 and 2 represent *design storms* associated with return periods between 1 and 5 years.
- RSI 3–5 cover *rare heavy rainstorms* with return periods between 10 and 30 years.
- Rainstorm severity indices 6–12 are assigned to rainstorm events above the 30-year return period, classified as *exceptional heavy rainstorms* in DWA (2016).

Within that concept, site-specific RSI values 1–7 can be assigned to corresponding rainfall depths and durations based on local heavy rainfall statistics or established duration-frequency curves.

5.2.2 | Assigning rainstorm severity index 8–12

The proper implementation of RSI values 8–12, intended to provide a distinct ranking of rainstorm events well above the 100-year return period, requires the perception of some upper limit of rainfall depths in the context of assigning severity index 12. Both, the concepts of probable maximum precipitation, for example, discussed in Kunkel et al. (2013) and WMO (2009), and practically relevant extreme precipitation values (PEN), established by Verworn and Draschoff (2008), highlight the range of possible maximum rainfall depths for distinct rainfall durations. Based on the analysis of these data, increase factors have been derived to generally describe progress of rainfall depths with increasing return periods well above the 100-year period. The increase factors are used to extrapolate extreme rainfall depths for the assignment to RSI 8–12 in reference to site-specific 100-year rainfall depths. As stated above, RSI 7 is pinned to the

TABLE 2 Extrapolation factors to specify site-specific rainfall depths for rainstorm severity index (RSI) 8–12, exemplifying for KOSTRA-DWD-2010 (DWD, 2010)[a], grid cell S16-Z75 and durations up to 6 hr

	$T_n = 100$ years					
RSI	**7**	**8**	**9**	**10**	**11**	**12**
Extrapolation factors	**(1.0)**	**1.2–1.4**	**1.4–1.6**	**1.6–2.2**	**2.2–2.8**	**>2,8**
Rainfall duration	**Rainfall depths for the S16-Z42 grid in mm (rounded off)**					
15 min	30	35–40	40–50	50–65	65–85	>85
1 hr	50	60–70	70–80	80–110	110–140	>140
2 hr	55	65–75	75–90	90–120	120–150	>150
4 hr	65	80–90	90–105	105–145	145–180	>180
6 hr	70	85–100	95–110	110–155	155–195	>195

[a] KOSTRA-DWD 2010 is the German standard database for heavy rainfall statistics (according to IDF curves) providing tables with relations between rainfall duration, frequency and intensity (spatial resolution of grid cells: approx. 8.5 km).

100-year rainfall as anchor value. To support the assignment procedure, the analysis of the PEN-LAWA database showed that rainfall depths of the 10,000-year return period coincide well with the range of generalized rainfall depths assigned to RSI 10 in the RSI12 concept, suggested by Schmitt (2015). This perception provided an additional guidance in the specification of extrapolation factors for that purpose.

For illustration purposes, Table 2 lists the extrapolation factors derived to assign site-specific rainfall depths to RSI 8–12 within the RSI12 concept. They are suggested as generalized values for rainfall periods between 15 min and 6 hr, most relevant in urban drainage design and flood risk management considerations.

Using the site-specific 100-year rainfall depths as anchor values, the rainfall data assigned to RSI 8–12 are provided as a range of rounded-off rainfall depths. Accordingly, the rainfall depths observed in the city of Münster in July 2014, 200 mm within less than 2 hr and about 300 mm in 7 hr (Grüning & Grimm, 2015), would certainly be classified with severity index 12 in the RSI12 scheme. The same holds true for the torrential rainfall in Dortmund 2008, where also around 200 mm have been reported for a 2-hr period.

It should be noted further, that the range of extrapolation factors assigned to RSI 10 (1.6–2.2) very well matches the increase values identified for the 10,000-year return period in the analysis described above. The extrapolation factor for RSI12—suggested here as "above 2.8"—leads to rainfall depths still well below the multiples for maximum areal precipitation values MAP. These multiples of the 100-year rainfall have been reported in DVWK (1997) to be in the range of 3.5–4.0 for Germany. Referring the extreme event in Münster in July 2014, mentioned above, to these multiples of the 100-year rainfall depths clearly indicates that this rainstorm event actually delivered rainfall depths in the range of maximum areal precipitation.

6 | CONCLUSION

The overview presented to characterize the evaluation and communication of pluvial flood risks in urban areas clearly indicates that PFRM has become a new and challenging task for municipalities. The discussion on possible effects of climate change on future extreme rainfall intensities and reports on pluvial flooding caused by extraordinary high rainfall depths have both have impacts on planning and operating of urban drainage systems. The design-oriented assessment of the system's hydraulic capacity has been supplemented by risk management considerations. Methodical flood hazard analyses are well understood to be the core element of PFRM and a major task in the near future for political decision makers, municipal administrations and drainage experts as well. Methodical approaches to carry out these analyses are well-established and the required database should be available in most cities as GIS-based DSMs. These methods are subject to practical applications at least in a pilot study phase, but more scientific work is needed to improve the validity and accuracy of analysis results.

As an example, the German guidelines DWA-M 119 have been outlined on the first hand to illustrate the scope of different methods of flood hazard analysis, but also to clarify the discrepancy in validity and significance between flood hazard and vulnerability analysis and risk assessments.

The survey on the current state of the art in PFRM carried out in Germany confirmed that flood hazard analysis has become a well-accepted method already and quite some cities have carried city-wide analyses. It also showed the discrepancy in data availability and methodical approaches for vulnerability and actual flood risk assessments. Only a few cities have implemented flood hazard or flood risk maps available for the public. This is at least partly due to concerns about protection of data privacy.

Within PFRM it is common sense that risk communication will play a key role to succeed in better flood prevention actions. To accomplish some understanding of the character of extreme rainfall events outside the community of meteorological and hydrological experts, it seems necessary to establish a new way of communication to gain a better perception of the character of extreme rainfall events. Based on this comprehension the concept of RSI has been suggested and presented in this paper. RSI values characterize the "magnitude" and "severity" of rainfall events rather than their rarity. The assignment of statistical return periods is hard to understand by non-experts, especially when the "100-year rainfall" seems to occur twice a year.

The further development and improvement of both, necessary databases and appropriate methods will be subject to research work and practical applications as well in order to further establish PFRM as an essential requirement and basis for—in the long term—flood resilient communities.

ACKNOWLEDGMENTS

Special thanks to the group members of DWA-AG ES-2.5 and their chairman Klaus Krieger.

CONFLICT OF INTEREST

The authors have declared no conflicts of interest for this article.

AUTHOR CONTRIBUTIONS

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How to cite this article: Schmitt TG, Scheid C. Evaluation and communication of pluvial flood risks in urban areas. *WIREs Water*. 2020;7:e1401. https://doi.org/10.1002/wat2.1401